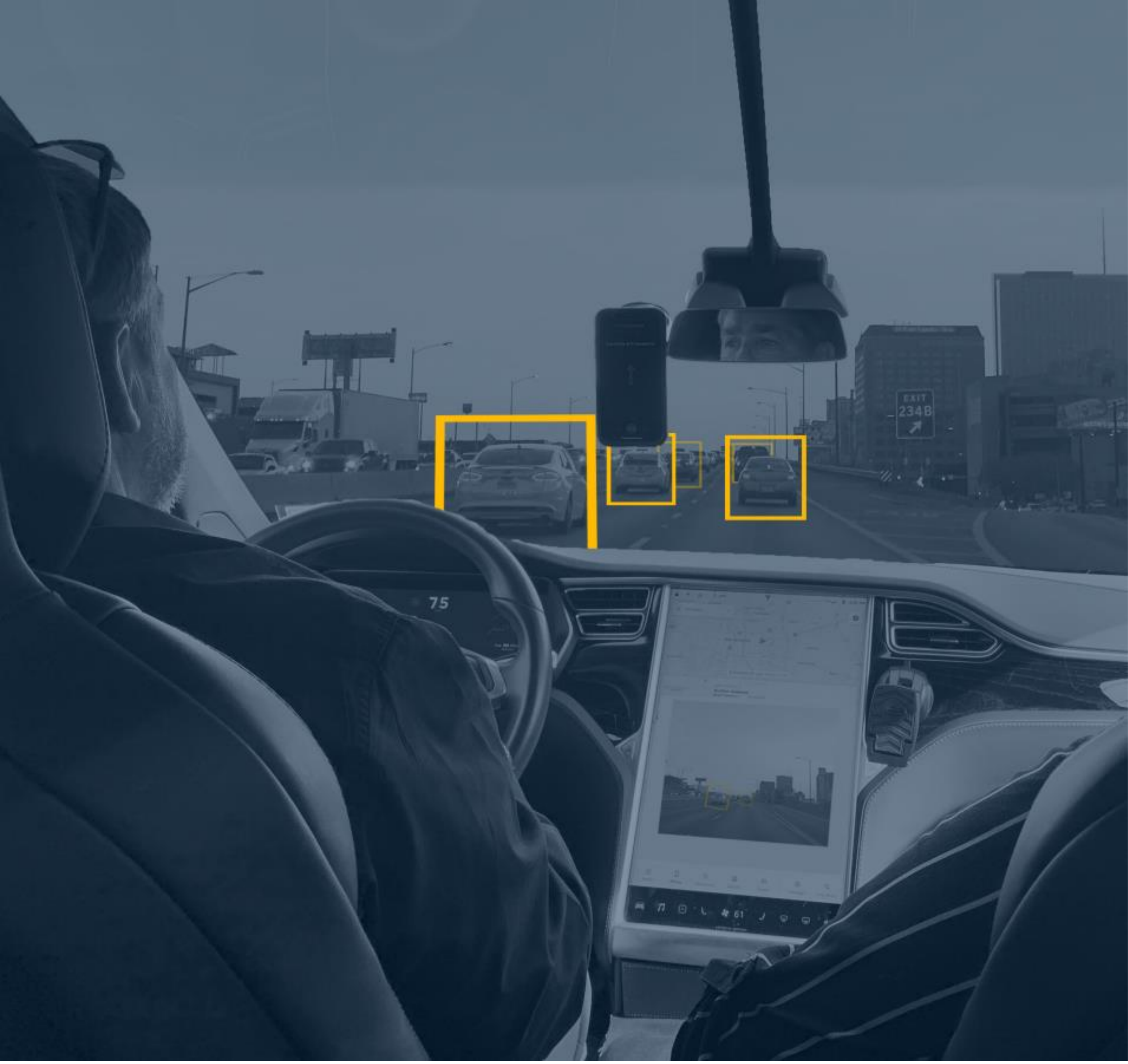

Automated Vehicle Recommendations for Texas:

A Study of Highway and Urban Operational Design Domains

TxDOT Project No. 0-7033

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16. Abstract

Automated vehicles (AVs) present significant potential; yet, their technological maturity and performance remain to be proven. With several deployments underway in the state, it is critical for the Texas Department of Transportation (TxDOT) to provide the public with assurances that the AVs are performing safely in their intended operational environment, the operational design domain (ODD). There is, however, no consensus on how AV safety should be evaluated, what metrics define AV performance, who should oversee the process, or even a common language to facilitate public-private dialogue. This project seeks to address these important questions in order to guide TxDOT in making future regulatory and investment decisions. In the first of two reports, there were three key findings. First, the research team defined a common ODD framework for Texas. Second, the research team identified several roadway environments with early deployments and ten problematic environments for special consideration; ultimately the research recommended two scenarios – forced merge and weaving response in both highway and urban downtown environments – for testing and simulation in the second phase of this project. Finally, the research team engaged a broad network of stakeholders to assist with formulating a safety assessment process that is both business-friendly and ensures public safety. The project culminates in this second report of technical and policy recommendations, enabling TxDOT to improve infrastructure readiness and guide forward-thinking policies.

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AUTOMATED VEHICLE RECOMMENDATIONS FOR TEXAS

A Study of Highway and Urban Operational Design Domains

EXECUTIVE SUMMARY

With significant safety and mobility benefits, automated vehicles (AVs) will be part of the future transportation system. Yet, there is no consensus regarding the method or the metrics to provide the public with adequate safety assurance. This research project studies some important questions that must be addressed as AV technology continues to mature and identifies opportunities for the Texas Department of Transportation (TxDOT) to guide future regulatory and investment decisions.

First, a common operational design domain (ODD) framework is defined to serve as the basis for public-private collaboration. In Texas, AV deployments are already underway—testing long-haul freight on major interstates, low-speed shuttles on university campuses, passenger service on local roads, and even last-mile deliveries on neighborhood streets. Each of these deployment environments, or ODDs, has different characteristics and therefore different design requirements. The research team proposes an ODD framework that highlights the elements and parameters of greatest relevance to TxDOT.

Second, the research team engaged a network of stakeholders to prioritize and select five scenarios for testing and simulation. Using sophisticated software and modeling tools, the research team created highway and urban downtown virtual environments, programmed an automated test vehicle, and designed experiments to compare automated and human driving behaviors in forced merge and weaving response situations. Over 20 participants were recruited for testing. The research team analyzed the results in order to draw conclusions related to safety, traffic operations, and human factors.

Finally, the research team synthesized the information to formulate policy and technical recommendations. While the National Highway Traffic Safety Administration (NHTSA) encourages entities to publish a Voluntary Safety Self-Assessment, Texas needs to be informed of new standards and regulatory developments. As the technology continues to mature, Texas can take steps to create a safe and business-friendly regulatory environment

This research report captures the highlights from TxDOT Project 0-7033 *Defining ODDs for the Safe Blending of Levels 0-4 Connected and Autonomous Vehicles (CAVs) in the Traffic Stream*. The report concludes with a research roadmap, identifying areas for further study that can guide TxDOT in improving infrastructure readiness and informing forward-thinking policies.

1 | INTRODUCTION

Automated Vehicles: The Need for Safety Assessment

Automated vehicles (AVs) present significant potential to improve roadway safety; yet, their technological maturity and performance remain to be proven. As a leader in AV deployment, Texas has a keen interest in safely advancing AV technology. With several deployments already underway, it is critical for the Texas Department of Transportation (TxDOT) to provide the public with the assurance that the AVs are performing safely in their intended operational environment—the operational design domain (ODD). There is, however, no consensus on how AV safety should be evaluated, performance metrics, who should oversee the process, or even a common language to facilitate public-private dialogue.

Project Overview

The University of Texas at Austin Center for Transportation Research (CTR) partnered with the Mobility Systems Lab to address these research gaps. The project's purpose is threefold:

- Define the ODD framework to describe the operational environment of an AV
- Evaluate AV performance by simulating AV operations in multiple scenarios
- Formulate policy, technical, and research recommendations for Texas

Explore. First, the research team conducted a literature review and engaged a broad network of stakeholders to assist with formulating a safety assessment process that is business-friendly and ensures public safety. Stakeholder feedback revealed advantages and disadvantages to the current voluntary safety self-assessment process and informed policy guidance for Texas in the next phase.

Develop. The research team defined a common ODD framework for Texas, highlighting the elements and parameters of greatest relevance to TxDOT. The research team identified several roadway environments with early deployments and ten problematic environments for special consideration. Based on input from a network of stakeholders, the research team selected five scenarios for testing and simulation.

Test and Simulate. The research team developed the scenarios by creating virtual highway and urban environments, programming the automated vehicles, and configuring the scenarios to compare automated vehicles to human driving behavior. The research team recruited 27 participants, who tested the scenarios in automated and manual driving modes. Having developed a performance metric framework, the research team analyzed the safety, mobility, and human-factors results from each of the test participants to draw conclusions.

Recommend. Finally, the research team synthesized the information and formulated technical, policy, and research recommendations, which enable TxDOT to improve infrastructure readiness and inform forward-thinking policies. As a result of this project, TxDOT is better positioned to guide the state in making future regulatory and investment decisions.

Society of Automotive Engineers (SAE) Levels of Automation

L0	L1	L2	L3	L4	L5
No Automation	**Driver Assistance**	**Partial Automation**	**Conditional Automation**	**High Automation**	**Full Automation**
Zero autonomy; the driver performs all driving tasks.	Vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design.	Vehicle has combined automated functions, but driver must remain engaged with driving task and monitor environment.	Driver is a necessity; must be ready to take control of the vehicle at all times with notice.	Vehicle is capable of performing all driving functions under certain conditions. Driver may have option to control the vehicle.	Vehicle is capable of performing all driving functions under all conditions. Driver may have option to control the vehicle.

Operational Design Domain (ODD)

The ODD describes the specific conditions in which the AV is designed to function, ensuring that the AV will perform adequately on the road. It can be considered a ***safety checklist*** that the vehicle must constantly complete in order to continue driving. If the vehicle fails to meet any of the criteria on the checklist, it is operating outside of its ODD and transitions itself to a minimal risk condition (e.g., pulling the vehicle over and bringing it to a safe stop). The research team developed an ODD taxonomy comprised of six categories.

Traffic Characteristics. Speed, traffic flow, and traffic mix.

Roadway Geometry. Horizontal and vertical alignment; grade separations; interchanges/ intersections; and cross-sectional elements.

Infrastructure Quality. Markings, signage, pavement condition, signals, and illumination.

Environmental & Weather Conditions. Weather conditions, particulate matter, and angle of sun/time of day.

Geographic Constraints. Pre-mapped, geofenced, and special zones.

Objects & Events. Typical and atypical objects, behavior, and operator interactions.

2 | THE TEXAS LANDSCAPE

TxDOT Advances CAV Efforts

In 2022, there were more than 4,500 deaths on Texas roadways. TxDOT has taken several steps to address the increase in roadway deaths, starting with a commitment from the Texas Transportation Commission to end all traffic fatalities by 2050. With a worthy and ambitious goal established, TxDOT has developed a suite of connected and autonomous (CAV) initiatives to take advantage of the technology's potential safety benefits.

In particular, TxDOT launched the CAV Task Force at the direction of Governor Greg Abbott. The CAV Task Force is composed of state, regional, and local agencies; industry representatives; and research institutions. It serves as a central resource for coordinating all ongoing CAV projects, investments, and initiatives in the state. In spring 2023, the CAV Task Force published its latest series of white papers, which identified several challenges and opportunities facing CAV deployments in Texas.

Additionally, TxDOT has established a Cooperative and Automated Transportation (CAT) Office, which will oversee the continued evolution of the CAT Strategic and Program Plans. The CAT Strategic Plan has identified 35 strategies across the agency to advance the goals of safety, mobility, reliability, agility, and vitality. development of a CAT Plan to integrate CAVs and related emerging transportation technologies into the state's transportation system.

Furthermore, TxDOT is establishing an innovation corridor program that will examine how to layer CAV technologies with alternative fuels, big data, unmanned aerial systems, and other emerging technologies. With efforts such as the Texas Connected Freight Corridors project already underway, TxDOT can leverage existing deployments to build a broader network across the state.

The outcomes of this research project will guide TxDOT in leading the CAV Task Force, raise awareness around safety policy, and inform future investment decisions.

Market Shifts

Despite AV's relative newness on the market, the AV revolution has already undergone disinvestment and consolidation. Monitoring market ebbs and flows is critical for TxDOT to ensure that the Texas market is progressing steadily and safely. Disruptions to the market may indicate a shift in public perception, that regulatory changes are required, or a pivot in economic investment.

Consolidation

While AV startups have made great strides in advancing the technology and preparing the regulatory environment, a sustainable business case has yet to be proven. In October 2022, Argo AI unexpectedly shut down. The company—backed by major OEMs Ford and Volkswagen—was testing in Austin and preparing for passenger service; however, Ford determined that fully autonomous vehicles at scale are not viable in the short-term and has instead chosen to concentrate its resources on lower-level advanced driver assistance systems (ADAS). This market shift indicates that ADAS technologies are more likely to see higher rates of public adoption in the personal vehicle market.

Another major player, Embark Trucks, is running short on capital and, after cutting over 70 percent of its workforce and shutting down two offices, is on a trajectory to close. The boom and bust from a $5 billion valuation to shuttered doors in 16 months demonstrates the volatility and struggle to establish a sustainable business plan. Like any venture, AV startups require a return on investment to continue operation and some companies have been slower than others to deliver. To cultivate a healthy business environment for AV startups, Texas may consider economic incentives and establishing a strong public-private partnership network that can aid with go-to-market strategies.

Expansion along Highways

While some companies have closed, others are expanding across the state. Several long-haul automated trucking companies have opened offices in Texas and are currently operating on TxDOT's highway infrastructure. In particular, TuSimple, Kodiak Robotics, Aurora Innovation, and Waymo are operating long-haul runs along the Texas Triangle, on I-45 from Houston to Dallas, I-30 between Dallas and Fort Worth, and along I-20 from Fort Worth to El Paso.

Additionally, automated short-haul operations are expanding. The medium-duty trucking company Gatik has opened a facility in the AllianceTexas Mobility Innovation Zone, alongside other automated long-haul operators. Gatik has partnered with Georgia-Pacific Manufacturing for automated delivery to 34 Sam's Club stores in the Dallas-Fort Worth area and announced a collaboration with Kroger to transport customer orders within the Dallas distribution network. As e-commerce continues to grow, more and more segments of the supply chain are likely to become automated.

Texas is also seeing an increase in the number of personal vehicles that are equipped with ADAS on its highways. Technologies such as lane centering, adaptive cruise control (ACC), and traffic jam assist have been deployed by OEMs onto Texas roadways. ADAS technologies, however, are not always used appropriately. For example, Tesla vehicles enabled with "Autopilot" have been shown to be spoofed in a way that allows the driver to disengage. As more AV technologies emerge, Texas should consider both the safety benefits as well as the risks.

Growth in Urban Settings

With five of the most populous cities in the country, Texas urban areas are seeing increased AV deployments. Partnering with Lyft, Cruise has soft-launched a fleet of fully driverless taxis in Austin. Also, the City of Arlington was awarded a Federal Transit Administration (FTA) grant to integrate May Mobility shuttle services onto its Via platform that had incorporated five AVs into its existing on-demand public transit service in March 2021. Houston METRO has also tested a low-speed shuttle that operates as a circulator on the Texas Southern University campus and will progress onto city streets to connect into its light rail system.

For freight and delivery, Nuro and Udelv are testing on-street, last-mile grocery delivery in the Houston and San Antonio regions, respectively. There are also several AV deployments that operate on sidewalks. In 2019, Starship Technologies deployed 30 personal delivery devices (PDDs)—autonomous robot couriers—at the University of Houston campus. Refraction AI began similar PDD programs for last-mile delivery in Austin in 2021. As cities become more crowded with different types of vehicles, Texas must consider how to safely manage the right-of-way.

Policy & Standards Updates

The research team reviewed the policy landscape and has captured significant updates in the federal, state, and industry realms.

Federal Policies

At the federal level, there are several adjustments being made to integrate AVs into safety regulations as well as increase transparency by collecting crash data.

When it comes to safety certification, USDOT is still asserting that companies conduct a self-certification and publish a voluntary safety self-assessment (VSSA). Currently, companies are required to self-certify compliance with the Federal Motor Vehicle Safety Standards. NHTSA encourages entities engaged in testing and deployment to publicly disclose a VSSA of their system across 12 different issue areas. The approaches, however, are highly varied and range greatly in their degrees of technical information.

NHTSA has issued a Standing General Order requiring identified manufacturers and operators to report to the agency certain crashes involving vehicles equipped with automated driving systems (ADS) or SAE Level 2 ADAS. In June 2022, NHTSA released its first report on AV crash data that summarizes crashes through May 15, 2022. The report revealed that 12 ADS and 80 ADAS crashes occurred in Texas. TxDOT can analyze the data further to identify potential infrastructure needs as well as areas to train first responders and law enforcement. Texas may also consider updating its crash reporting form (CR-3) to be in alignment with the Standing General Order and denote crashes involving vehicles with ADS and/or ADAS technologies.

State Policies

Developing policy around a rapidly changing technology is a complex task. The Texas Legislature has historically embraced AV technology, setting business-friendly regulatory conditions at the state level and providing clarity where laws are ambiguous. In Texas, two key pieces of legislation impact AV operations. In 2017, the 85th Texas Legislature passed Senate Bill (SB) 2205, which enables AVs to travel on any Texas roadway, transport passengers, and operate without a safety driver. The 85th Legislature also passed House Bill (HB) 100, which regulates transportation network companies (TNCs). HB 100 charges the Texas Department of Licensing and Regulation with overseeing TNCs, including AV services that carry passengers. As AV technology matures, Texas will need to continue evolving its policies to maintain its business-friendly regulatory environment and ensure public safety.

During the 88th Texas Legislature, HB 3274 was filed, requiring a human operator to be present in order to operate an autonomous vehicle. At the time of publication, the bill has not progressed. Similar bills are being filed in other states and the AV industry is closely monitoring, as it would have significant implications for when the safety operator could be removed to achieve driver-out operations.

Industry Standards

The private sector has continued to advance AV safety standards, focusing on methodology for defining and evaluating AV safety cases. UL 4600 continues to provide the basis for defining a safety case. Waymo has further built upon it by publishing an approach for determining the absence of unreasonable risk. Other companies are similarly advancing their own methodologies and Texas can engage in forums that are seeking to build consensus across the industry.

3 | PROCESS

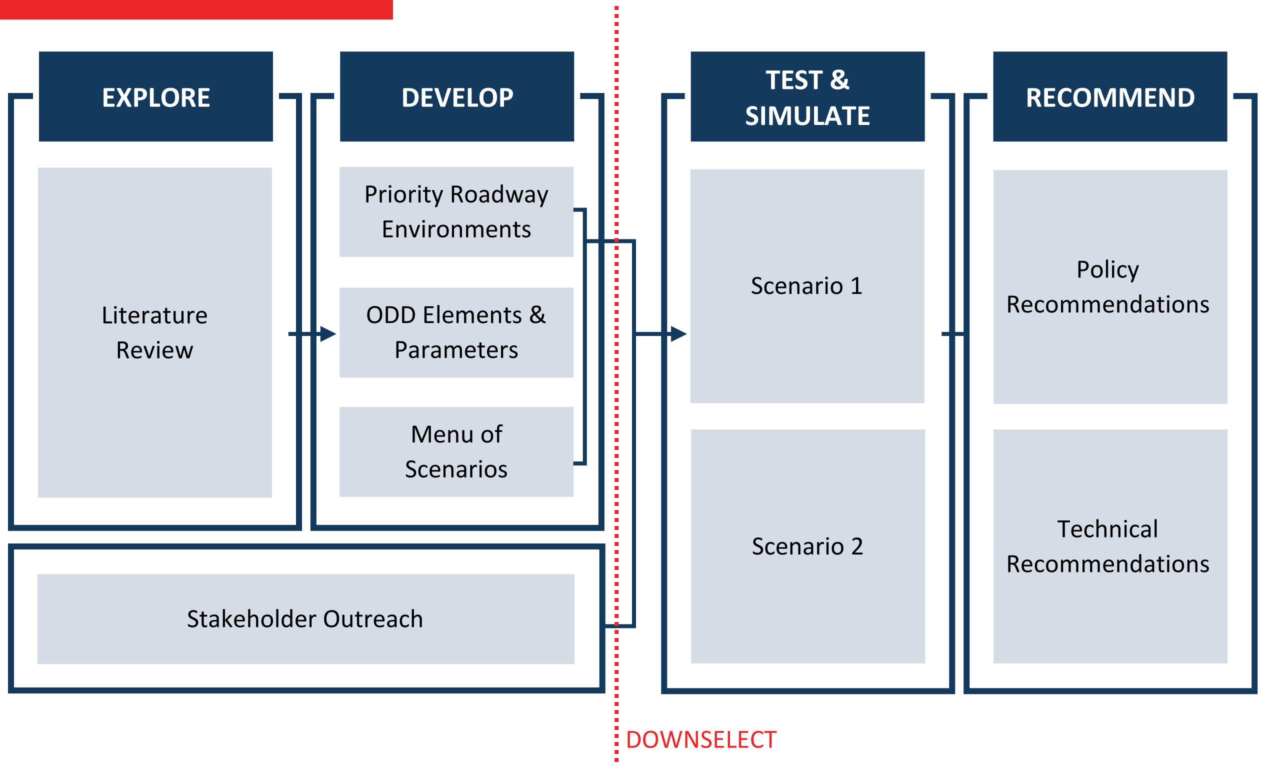

Figure 1: Project Components & Process

Launched in September 2019, Project 0-7033 *Defining ODDs for the Safe Blending of Levels 0-4 Connected and Autonomous Vehicles (CAVs) in the Traffic Stream* included four major stages (Figure 1):

Explore

First, the research team began by scanning academic literature, industry sources, and conducting key person interviews. This foundational step enabled the research team to become familiar with industry standards, federal policies in both the United States and abroad, and current gaps. In particular, the research team found a need for Texas to develop an ODD taxonomy and to improve the process for safety assurance.

Develop

Next, the research team identified and prioritized Texas roadway environments, proposed an ODD framework for Texas, and established a menu of scenarios for simulation. This phase culminated in the selection of five scenarios for testing and simulation.

Test & Simulate

The research team developed the two selected scenarios for testing and simulation, including building the roadway environment in virtual reality and programming individual vehicles. In addition, the research team invited participants to test each scenario and analyze the data for safety, mobility, and human factors insights.

Recommend

Finally, the research team formulated technical, policy, and research recommendations. Included is a summary of the results, comparing the performance of AVs in different scenarios. Furthermore, the recommendations will inform TxDOT on opportunities to evolve its roadway design and maintenance operations practices, guide policymaking, and increase public awareness.

Figure 2: Stakeholder Groups

Stakeholder Mapping & Prioritization

Gaining feedback and input from stakeholders is critical for the creation of state regulations and policies that do not stymie AV development. The research team began with a stakeholder mapping process, identifying a large body of stakeholders and organizing them based on the following areas of expertise (Figure 2):

- Industry & Original Equipment Manufacturers
- Insurance & Liability
- Think Tanks & Professional Societies
- Research Institutions

With these groups being spread across the US, and working in different fields, the amount of information shared between them can be limited, as proprietary technology and methods are found in each. To develop an ODD framework and identify candidate scenarios for simulation, the research team prioritized twelve organizations across the four categories for key person interviews. Through the interviews, the research team sought to gain further insights into their positions on ODDs, safety assessments, regulations, and actions that states can take to increase safety while not hampering AV development.

To kick-start discussions, the research team sent project primers in advance of the interviews. The primers explained 1) the state of practice in ODD utilization and 2) the research approach. In addition, the research team sent a tailored set of questions to guide each of the discussions.

By engaging such a broad network, the research team gained valuable information that will guide TxDOT as the agency makes informed infrastructure and policy decisions.

Priority Roadway Environments

With more than 680,000 lane miles, Texas presents a significant opportunity to test AV operations; yet it can be a challenge to categorize and prioritize Texas' roadway environments for infrastructure readiness investments. This section identifies five basic roadway environments, recommends two for testing and simulation, and highlights the ODD elements of greatest relevance to TxDOT.

Roadway Environments for Consideration

Several roadway environments were considered for testing and simulation: highway, managed lanes and toll roads, retail and office parks, neighborhood streets, and urban downtown. The major interstates are most likely to be early test beds for AV deployments, particularly for automated trucking. Rural highways are simpler roadway environments, with fewer lanes and lighter traffic patterns, but may not have a median. Urban highways and downtowns are more complex in that they typically have more lanes, higher traffic flows, and greater degrees of uncertainty related to wrong-way drivers, pedestrian crossings, and erratic behavior of other drivers on the roadway.

A Two-Pronged Approach: Studying Highway & Urban Environments

Based on stakeholder interviews and research value, the research team selected a two-pronged approach that involved studying both highway and urban downtown environments during the testing and simulation phase. Table 1 captures their key characteristics. These two roadway environments are recommended based on the value they would provide to TxDOT related to improvements to TxDOT roadway design and maintenance practices; awareness of safety factors for off-system AV operations; and opportunity to inform policy at the state and federal levels.

Problematic Roadway Environments

Beyond the typical roadway environments, there are edge cases of higher degrees of complexity that require special focus. Table 2 identifies ten problematic roadway environments for consideration in Texas. The research team prioritized the forced merge and weaving response for further examination during the testing and simulation phase

Table 1: Highway and Urban Downtown Characteristics

	HIGHWAY	URBAN DOWNTOWN
Traffic Characteristics	60 mph	35 mph
Roadway Geometry	On-/Off-Ramps, X-configuration interchanges	Parallel parking lanes, bus dwell areas, intersections
Infrastructure Quality	Simple signage and lane markings	Stop sign, crosswalks, turning lane markings
Value to TxDOT	Inform TxDOT roadway design and maintenance practices; partner to support automated freight testing; gain familiarity with highway AV capabilities	Increase understanding of complex operations; inform statewide policy; improve ability to conduct education and awareness efforts

Table 2: Problematic Roadway Environments & Events

Work Zones. One of the most difficult roadway environments to navigate due to unpredictable and complex roadway geometries and the unreliability and unpredictability of lane markings and road conditions.

Emergency Vehicle Response. Detecting lights and sirens is extremely complex. Improvements are needed to enable sensors to determine the speed, heading, and location of the emergency vehicle.

Nighttime Issues. Several operational challenges arise at night. Cameras cannot readily detect lane markings and may be blinded by oncoming headlamps. In addition, construction activities often take place at night and involve lane closures, tapers, and lane marking adjustments. Lastly, wildlife are more likely to unexpectedly appear on roads at night, affecting both human drivers and AVs.

On-/Off-Ramps. While there are standard configurations, the variety in entrance and exit ramp design makes navigation a challenge. In addition to the several exceptions to the design standards, such as steep slopes and quick merges, other road users may make aggressive maneuvers when entering or exiting roadway facilities.

Pedestrian Detection and Human Interaction. Interacting with pedestrians may involve informal gestures and nuanced signals, which can be difficult for AVs to interpret and communicate. Additional research is needed to predict pedestrian movements at crosswalks and to study AV sociolinguistics.

Adverse Weather. Heavy precipitation, snow, ice, fog, and dust can reduce the capabilities of several sensors simultaneously. Significant improvements to LiDAR, RADAR, camera, and ultrasonic systems are still needed to enable AVs to operate in adverse weather conditions.

Forced Merges. When a lane ends and forces a merge, it can be difficult for an AV to anticipate and change lanes, particularly in heavy traffic. Clear signage, advance notification, and gradual transitions would be beneficial.

Unpaved Roads. Without clear markings and signage, AV navigation systems struggle. With more than one-third of US roads being unpaved or lacking well-marked road edges, additional research is needed to improve operations.

Left Turns. Due to the uncertainty of oncoming vehicle maneuvers, left-turn planning is a formidable challenge for AVs, especially at unsignalized intersections. Further development is needed to improve the reliability of this maneuver.

Weavings. AVs must learn to react quickly to the unpredictable driver behavior found in weaving situations, i.e., when another vehicle acts aggressively by darting into the AV's lane, decreasing the headway the AV previously had between it and the vehicle in front of it.

ODD Elements & Parameters

To ensure that AVs are operating safely within their intended environment, environmental constraints must first be defined. Currently there is no single definition of what constitutes an ODD and, in fact, most AVs will employ a multitude of ODDs from trip beginning to end. Furthermore, the terms used to describe the elements of the ODD vary from organization to organization, making it difficult to communicate effectively, forge common safety metrics, or develop policy. To address these issues, the research team proposes formulating an ODD taxonomy for Texas. Figure 4 illustrates the proposed ODD framework based on literature review, industry standards, and alignment with TxDOT Roadway Design and Maintenance Operations Manuals.

The taxonomy is composed of six categories, which are in turn made up of elements and parameters. See below for an example:

- **Category**: Environmental & Weather Conditions
  - **Element**: Weather (rain)
    - **Parameter**: Droplet size (light, medium, heavy)

In particular, the research team emphasizes the subset of the ODD that constitutes the roadway environment—traffic characteristics, roadway geometry, and infrastructure quality—as having greatest relevance to TxDOT. Additionally, there are common objects and events—traffic cones, forced merges, etc.—that are also pertinent. The following describes each of the six categories and its respective elements in greater detail:

ROADWAY ENVIRONMENT

Traffic Characteristics

- Speed
- Traffic Flow
- Traffic Mix
  - Types of Vehicles
  - Levels of Automation

Roadway Geometry

- Road Type
- Horizontal/Vertical Alignment
- Grade Separations
- Interchanges/Intersections
- Cross-Sectional Elements
  - Number of Lanes
  - Lane and Shoulder Widths
  - Median Design

Infrastructure Quality

- Lane Markings
- Signage
- Pavement Conditions
- Traffic Signals
- Illumination

ADDITIONAL ELEMENTS

Environmental & Weather Conditions

- Weather (wind, precipitation, ice, etc.)
- Particulate Matter (fog, dust, etc.)
- Time of Day/Angle of Sun

Geographic Constraints

- Pre-mapped
- Geofenced
- Special Zones (school zone, work zone etc.)

ACTORS

Objects & Events

- Objects
  - Permanent Objects
  - Transient Objects
  - Atypical Objects
  - Other Road Users
- Events
  - Typical Behavior
  - Atypical Behavior
  - Operator Interactions

Figure 3: Proposed ODD Framework

Selected Scenarios

In navigating along its route, an AV will pass through several ODDs—operating at different speeds, navigating a variety of intersections, and interpreting the behavior of other road users.

Table 3: Selected Scenarios

#	Environment	Scenario
1a	Highway	Forced Merge
1b	Highway	Weaving Response
2a	Urban Downtown	Forced Merge
2b	Urban Downtown	Weaving Response
3	Highway	Dedicated Lane

Forced Merge

The research team simulated a forced merge with a lane drop, studying the effects of speed, traffic flow, and levels of automation. In particular, the research team focused on the forced merge under different traffic flows. For example, an AV forced to merge in free-flow traffic is able to easily maneuver into the adjacent lane; however, an AV operating in rush hour will find it difficult to assert itself and merge if adjacent vehicles do not create a sufficient gap.

Weaving Response

Weaving is a problematic event that increases the risk of collision. This scenario tested how the AV performs when another vehicle suddenly enters its travel stream while operating at different speeds—35 mph in the urban downtown and 60 mph on the highway. This scenario provides information to TxDOT on how quickly a human can adapt compared to an AV.

Dedicated AV Lane

The research team also studied operations of a dedicated AV lane, where the leftmost lane was dedicated to AVs. Two scenarios were tested—the first where there were no interruptions and the second where another vehicle disrupted the traffic flow of the dedicated lane by weaving in front of the ego test vehicle. This scenario provided further insights into infrastructure design and the risks associated with weaving traffic.

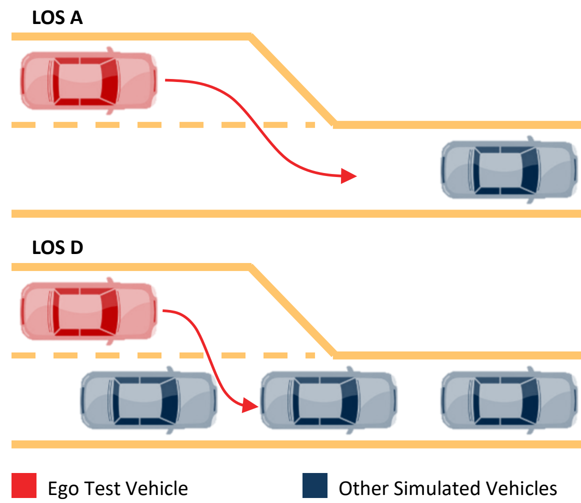

Figure 4: Forced Merge Scenario at Different Traffic Flows

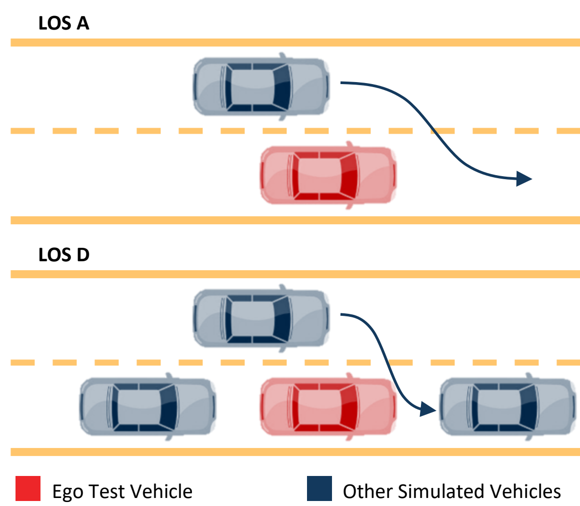

Figure 5: Weaving Scenario at Different Levels of Service

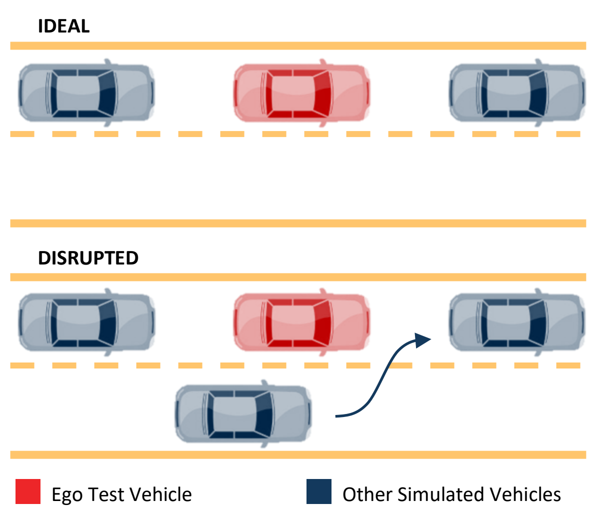

Figure 6: Dedicated Lane Scenarios

6 | TEST & SIMULATE

Simulation Development

The use of driving simulation is invaluable for the safe development of AVs to study how they will function in different ODDs. The research team used a sophisticated driving simulator, created the virtual environments, programmed the vehicles, and designed the testing experiments.

System Hardware

The driving simulator used in this research project has professional driver interface equipment, including a seat, pedals, and a steering wheel. It consists of a six-degree-of-freedom hexapod that uses stroke actuators to provide longitudinal, lateral, and vertical movement and yaw, pitch, and roll rotations. The system can also provide force feedback through the steering wheel by using a control loading motor to produce continuous torque. Auditory feedback (e.g., engine sound, tire friction, etc.) is also incorporated in the simulator by four surrounding speakers and one sound engine that lays below the simulator. This combination of the motion, haptic, and auditory feedback work simultaneously in an accurate and fast manner to establish a realistic driving experience for the human subjects.

Apart from the driving platform, the visual representation of the desired virtual environment is produced by three projectors that display the graphics on a 210-degree conical screen. The conical screen gives the driver a perception of being immersed in the virtual environment. All three projectors are synchronized to be updated in real time to maintain a small latency and establish a smooth transition between frames, decreasing the possibility that a human subject experiences a mismatch between graphics and motion.

System Software

The research team designed roadways that resemble those found in a highway and urban downtown environment. Using MathWorks RoadRunner, an interactive editor, the research team created three-dimensional scenes for testing the AVs. The research team gave the roadways a realistic look by using pre-built 3D models of road signs, signals, guardrails, buildings, and many more features.

The research team also used Autodesk 3ds Max, to enhance the environments with visual realism. Through various editing features, the research team added materials and textures with different reflectivity properties to create a dynamic real-world setting. The research team combined MathWorks RoadRunner and Autodesk 3ds Max to develop visually realistic highway and urban downtown environments.

Automotive Simuation Models

The research team used dSPACE Automotive Simulation Models (ASM) to program the test AVs. The particular ADAS features included in each level of automation are listed in Table 4.

Table 4: ADAS Features

ADAS Feature	L0	L1	L2	L3
Lane Departure Warning	X	X	X	X
Adaptive Cruise Control (ACC)		X	X	X
Lane Centering			X	X
Highway On-/Off-Ramp Assistance				X

Highway Configuration

The majority of TxDOT facilities may be represented by the highway environment, which was selected to provide TxDOT with insights into infrastructure needs, traffic characteristics, and driving behaviors that impact AVs. The highway environment was designed as a 15-mile-long, six-lane divided, controlled-access freeway that consists of six equally spaced x-configuration interchanges with one-way frontage roads on each side. The environment consists of typical characteristics that are found on Texas highways, including speed limit and entrance/exit ramp signage. Common lane markings were implemented in the environment and adhere to TxDOT's Roadway Design Manual. The geometric configuration consists of an at-grade facility that slopes upward as it approaches an interchange to produce an overpass, allowing the frontage roads on each side to connect underneath. After passing the interchange the highway returns to grade. This geometric configuration is continuously repeated for each interchange.

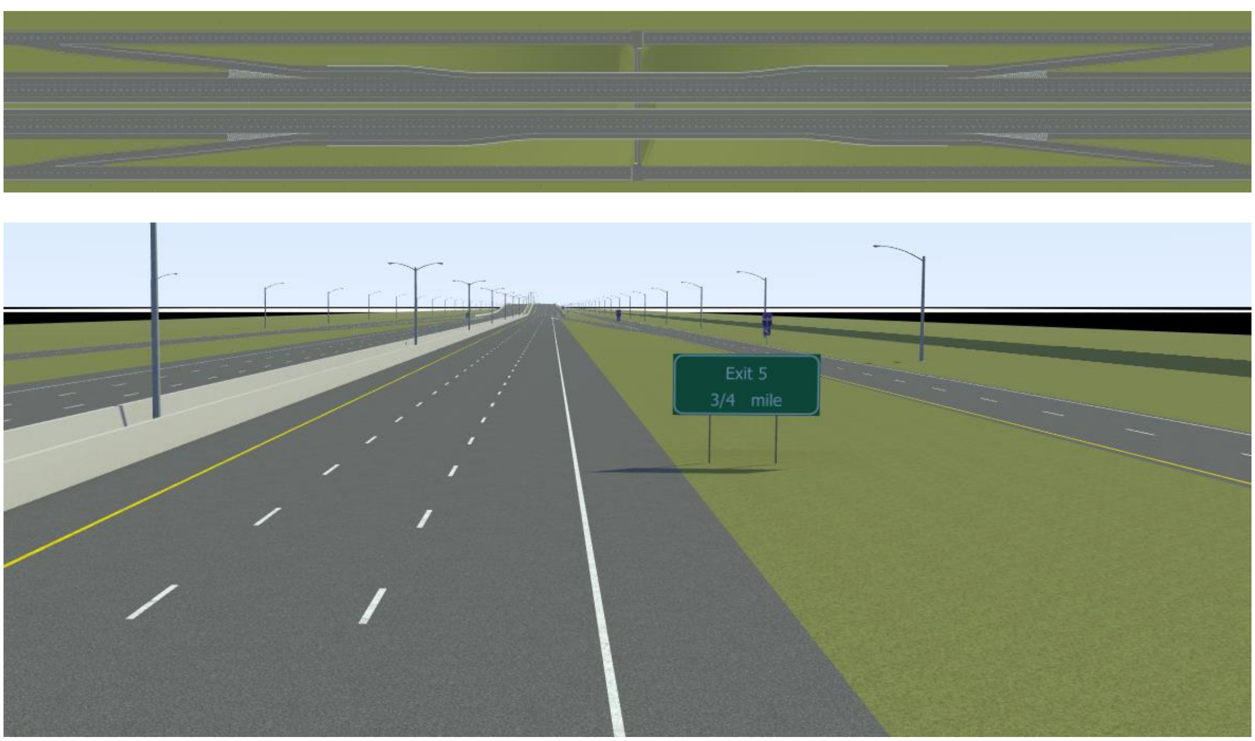

Figure 7: Highway Testing Environment

Urban Downtown Configuration

The urban environment was selected to provide TxDOT with insights into a more complex ODD, which can inform local infrastructure needs, safety investments, and state policy. The urban environment was designed as a six-block network that is surrounded by a circulating roadway and evenly divided by three intersecting roadways.

The environment consists of six features that are present in common urban settings: 1) Construction Zone, 2) Bus Dwell Area, 3) Stopped Bus, 4) Right Turn Only, 5) Parallel Parking, 6) Mid-Block Driveway. The stop sign in Figure 9 is representative of an urban intersection, and the construction zone in Figure 10 creates the forced merge and weaving response scenarios. All roads in the urban environment vary between two- to four-lane undivided facilities and are surrounded by urban buildings. While a realistic urban environment includes a certain level of pedestrian and cyclist activities, this project excludes these factors and instead focuses on collecting data and drawing conclusions around vehicle-to-vehicle interactions.

Figure 9: Stop Sign in Urban Test Environment

Figure 10: Work Zone in Urban Test Environment

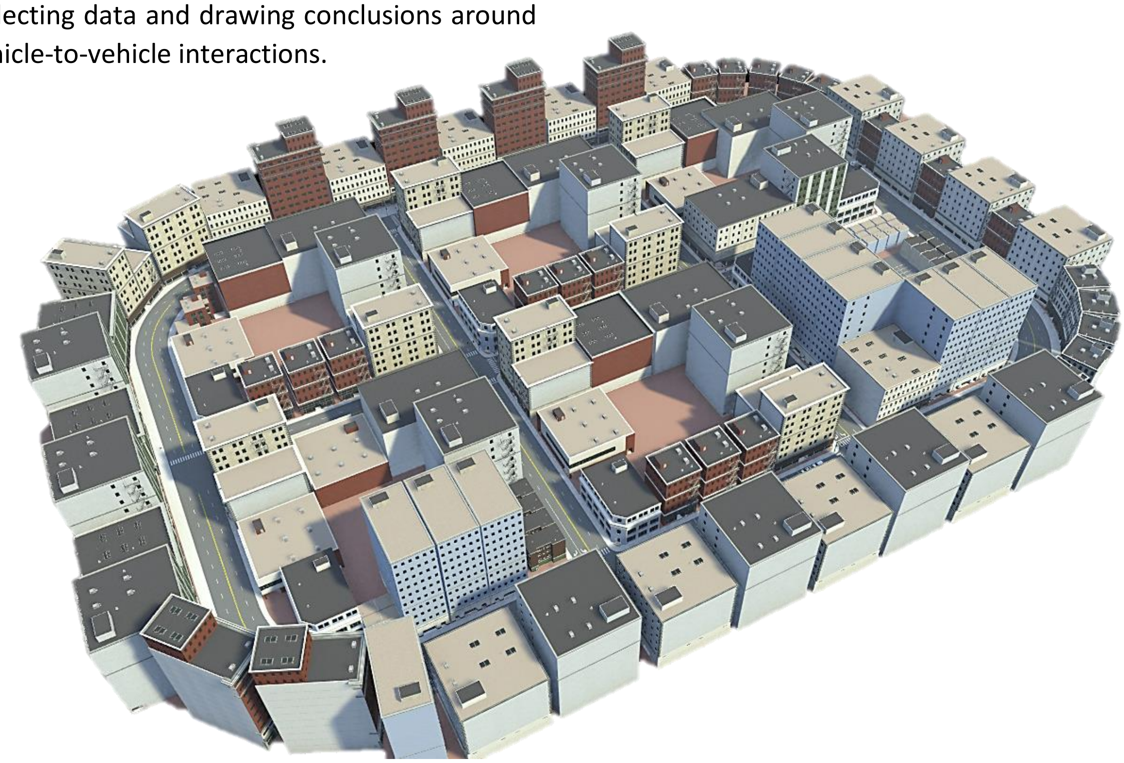

Figure 8: Urban Downtown Testing Environment

Experimental Design

Beta Testing

The beta testing phase included initial tests run by the research team to finalize the testing procedure. From prior research, the research team selected five scenarios for final testing: Highway—Forced Merge, Highway—Weaving Response, Urban—Forced Merge, Urban—Weaving, and Highway—Dedicated Lane.

Final Testing Design

Based on the trials conducted during beta testing, the research team set the total number of laps in the urban scenario and total highway intersections to be six. The researchers chose this number of laps to optimize data collection and time spent in the simulator.

From participant feedback during beta testing, the researchers determined that 20 minutes total in the simulator is the optimal time to prevent motion sickness and maintain the attention of the participant.

The research team also determined that the first three laps or intersections would be operated by the Level 3 (L3) automated driving system (ADS) and the remaining three to be Level 0 (L0) manually driven. The research team selected this order of ADS first and manual second so that the human driver has an opportunity to see how the scenario is designed to be run and they then replicate that to the best of their ability.

Lastly, the research team adjusted headways and spacing of vehicles to better represent the different levels of traffic at level of service (LOS) A and LOS D.

Participant Recruiting

Participant Groups

The researchers recruited test participants from three categories. The first category is University of Texas at Austin students who work for the Center for Transportation Research (CTR) and the Mobility Systems Lab. These students are the first participants to run the simulator with their driving data included in the final research. These participants were specifically recruited as they had some familiarity with AVs. They are also well suited to offer feedback on the logistics of recruiting drivers, outlining the requirements for drivers, and workshopping the user survey. The second category is Texas Department of Transportation (TxDOT) employees familiar with the project. The last category is members of the general public. This last category is designed to be a sample that is representative of the broader Texas demographics.

Recruitment Methods

The researchers used word of mouth and email to recruit from the first two categories. The researchers used a flyer advertising the $25 reimbursement for participants for recruiting the general public. The researchers distributed the flyer across various UT organizations and to social networks.

Participant Orientation

The research team created testing materials to assist in orienting test participants and for data collection. The first test material is a poster that outlines the objectives of the project, an illustration of the components of the simulator, an overview of the four scenarios to test, and a QR code link to the user survey (a Google form survey). The survey collects participant demographic information and includes sections on how the AV performed, the comfortability level, and motion sickness.

Safety Analysis

Texas is keenly interested in the potential safety benefits of AVs. As more Texans purchase vehicles with ADAS features, it will be important for TxDOT to understand how effective they are in comparison to human driving behaviors.

Key Performance Metrics

The research team studied the following key performance metrics:

- **Time-to-Collision (TTC).** The time required for two vehicles to collide if they continue at their present speed and on the same path.
- **Headway.** Distance between vehicles in the same lane.
- **Lateral Offset.** Distance between the ego test vehicle's center of gravity to the centerline of the lane in which it is traveling.

Analysis

While the results showed that, on average, the human participants were safe, the ADS was safer in every performance metric.

Beginning with the TTC, human participants drove more aggressively than the ADS in the Urban—Forced Merge, Urban—Weaving Response, and Highway—Weaving Response scenarios—as evidenced by their lower TTC values. On the other hand, human participants drove more cautiously in the Highway—Forced Merge scenario. This behavior reflects the caution that humans apply when merging into a mainlane from an on-ramp. In fact, one participant displayed such caution in the Highway—Forced Merge scenario that he maximized the TTC and disengaged from traffic flow. Overall, the ACC feature was successful in increasing the TTC and safety in the majority of scenarios and could be refined to better accommodate highway forced merge scenarios.

The headways match this pattern and represent the distance between the ego test vehicle and the vehicle in front of it. Focusing on the change in LOS, the human driver and ADS headways decreased consistent with the traffic flow increasing from LOS A to LOS D. That is, the human participants decreased their following distance by 7-12 meters on the highway and 6-10 meters in the urban downtown when entering the LOS D conditions; similarly, the ADS decreased its following distance by 11-12 meters on the highway and 8-9 meters in the urban downtown upon entering LOS D. The ACC feature is effective in maintaining a consistent following distance, thereby increasing the headway, time-to-collision, and occupant safety.

The lateral offset is key to determining the distance that a vehicle swerves from the lane's centerline. Of note is that human participants across all scenarios deviated an average of 0.4 meters and a maximum of 2.0 meters, which is half of the lane width. The human drivers regularly crossed the lane boundaries, while the ADS maintained its position within the lane and was consistently centered—displaying an average lateral offset of 0.04 meters and a maximum lateral offset of 0.25 meters. The lane centering feature therefore proves valuable in reducing lateral collision risks.

Takeaways

While the experimental results show that on average the human drivers were safe, the ADS was safer than the human driver across all safety performance metrics:

- Time-to-collision
- Headway
- Lateral Offset

Traffic Flow Analysis

With limited resources, Texas recognizes the need to optimize its existing roadway infrastructure. Beyond safety, another potential benefit of AVs is the ability to smooth traffic and reduce congestion.

Key Performance Metrics

The research team studied the following key performance metrics:

- **Variance of Velocity.** Variability from the average velocity; used to determine the smoothness of the vehicle in traffic.
- **Mean Delay.** Difference in actual and theoretical travel time at free-flow speed.
- **Total Stopping Time.** Total duration of time during which the vehicle's speed is zero or very close to zero.

Analysis

The ADS demonstrated significant benefits in optimizing traffic flow over the human drivers. When comparing the velocity profiles in Figure 11, the ADS produces a significantly smoother experience than a human driver, which is attributed to its advanced sensing and control algorithms. On the other hand, human drivers oscillate their velocity to a much higher degree, contributing to traffic shockwaves.

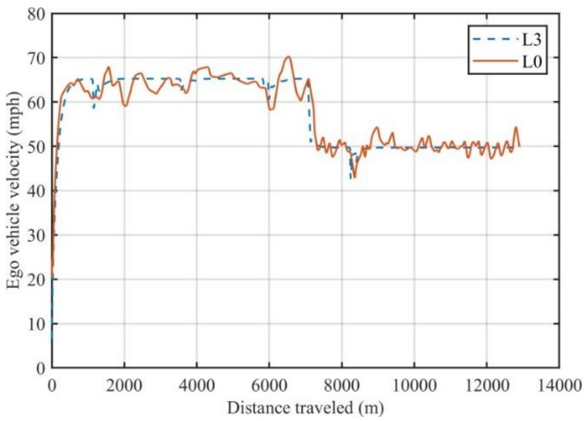

Figure 11: Velocity Profiles of ADS (L3) and Human Driver (L0) in Highway—Forced Merge Scenario

The variance in velocity quantifies the fluctuations in speed. The ADS reduced the variance in velocity for nearly all test participants. In other words, the ACC feature improved the velocity profile of the vehicle and smoothed traffic flow. For two participants in particular, the ACC reduced the variance in velocity three- and fourfold. ACC also proved most effective in the Highway—Dedicated Lane scenario where there were no disruptions to the traffic stream.

Focusing on highway congestion, the Highway On-/Off-Ramp Assistance feature reduced the mean delay for the majority of human drivers in the Highway—Forced Merge scenario by a few seconds. While the time savings is limited for a single vehicle on a short test run, the reductions in delay can have broader impacts when extrapolated to longer trips and thousands of vehicles. Furthermore, the highway on-/off-ramp assistance feature smoothed the traffic during each of the conflict points, contributing to lower congestion as well as improved safety.

Turning to the urban downtown, the research team focused on total stopping time. In particular, the research team compared the human behavior at a stop sign intersection to the ADS and found that all human participants stopped shorter than the three seconds required by Texas regulation. Since AVs will be programmed to obey all traffic laws, TxDOT can develop education programs to inform the public about AVs operating on Texas roadways.

Takeaways

The experimental results show that traffic flow can be improved using ACC. A smoother speed profile can have positive benefits on the following:

- Reducing congesting
- Improving traffic flow
- Reducing emissions

Human Factors Analysis

Human factors is a critical area of research in order to understand the public's knowledge and comfort of AVs. The research team conducted an exit survey of all test participants in addition to analyzing the simulator results.

The survey included demographics information. Most of the test participants were between the ages of 16 to 25 years old, with the next largest age group being 26 to 35 years old. The participants were mostly male and represented a range of ethnicities. The majority of participants drive 10,000 to 15,000 miles annually and were therefore familiar with driving. Additionally, the research team asked participants to provide feedback on their comfort level with the ADAS features, and over 78 percent were somewhat to very comfortable with the lane centering. Future research may consider expanding the test group to include more diverse age groups and AV knowledge levels.

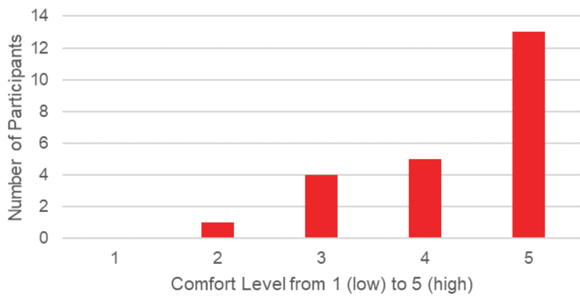

Figure 12: Participant Comfort Level with the Lane Centering ADAS Feature

Key Performance Metrics

The research team studied the following key performance metrics:

- **Takeover Frequency.** Total number of disengagements divided by the duration of the test.
- **Miles per Disengagement.** Total number of disengagements divided by the mileage traveled by the vehicle.
- **Driver Reaction Time.** Reaction time of the driver to an incident.

Analysis

There were no takeovers or disengagements in the initial test runs. Therefore, the research team refined the experimental design process to include a forced takeover scenario that would measure the human participant's responsiveness. A new component was added to the Urban—Weaving Response scenario where an alert was activated when another vehicle attempted to merge into the ego test vehicle's lane. The alert was delivered both visually and audibly, flashing a red warning on the touchscreen in the driving simulator's cockpit instructing the driver to take over as well as sounding a beeping noise.

Three test participants were recruited to test the modified Urban—Weaving Response scenario with the takeover alert system. The modified scenario consisted of a single lap, instead of six, and no advance warning was given to the test participants. The three participants regained control of the vehicle in under 1.8 seconds.

The research team recommends that this scenario be expanded to a larger test group as well as increase the number of laps in order to measure driver reaction time after extended periods of automation. This type of testing could investigate the dangers of automation complacency, where humans may rely on the technology to a point where develop a false sense of security.

Takeaways

Preliminary test results showed human driver reaction time of 1-2 seconds when presented with a takeover alert. Further human factors research is needed to test:

- Automation complacency
- Alert methods (visual, audio, haptic)
-

Policy Recommendations

There have been several developments in the connected and autonomous vehicle technologies that are prompting policymakers to act. Furthermore, Texas has created an attractive market with its business-friendly regulatory environment. Historically, the Texas legislature has sought to offer clarity and remove regulatory barriers when identified, making Texas a leader in the deployment of automated vehicle technologies. In alignment with this approach, the research team focused on key areas to assist TxDOT in its guidance to the Texas legislature, including terminology, policy best practices, and safety standards. The following recommendations have been developed:

Texas must develop a strong safety culture among its AV community. As verification and validation methodologies continue to evolve, Texas may consider developing its own voluntary safety self-assessments, participating in standards development, or combining independent safety reviews to supplement self-certification.

Involve public and private stakeholders in developing AV policy and infrastructure guidance. By incorporating stakeholder feedback, Texas can gain information on how the various stakeholder groups view ODDs, safety assessments and regulations, and what policies the state can adopt to increase safety while not constraining AV development.

Prioritize highway and urban downtown environments for testing and simulation. The research team recommends developing the highway and urban downtown environments for testing and simulation. Working with these two environments will enable TxDOT to learn information at different traffic speeds, study a range of simple and complex environments, and create a knowledge base to inform statewide policies that will affect roadways both on and off TxDOT's system.

Develop a common ODD framework. As the number of deployments, technologies, and operational environments continue to grow and diversify, a common ODD framework will be fundamental for public-private collaboration. The proposed framework is aligned with TxDOT's Roadway Design and Maintenance Operations Manuals and emphasizes the elements of greatest relevance to infrastructure owners and operators.

Focus on forced merge and weaving scenarios to learn about infrastructure and human behavior. Through testing and simulation, the research team will study how an AV performs under different speeds, traffic flows, and levels of automation in this project. In particular, the forced merges scenario will enable the research team to study how roadway geometry at a lane drop affect AV performance. In addition, the research team plans to study weaving behavior and measure the benefit of automatic braking technology compared with human reaction times.

Promote dialogue and data sharing among public and private stakeholders. Texas has the opportunity to continue to promote discussions and the sharing of information among AV stakeholders. Due to liability and intellectual property protection, AVs are being developed utilizing different approaches, creating difficulty in regulating and understanding how these vehicles operate. Promoting the collaborative sharing of data and information on the development of AVs can benefit not only Texas but other states in the creation of a unified approach to safety assessment.

Technical Recommendations

In addition to policy recommendations, the research team has identified several technical recommendations. These recommendations come from the experimental results and highlight areas for further research, advancements for safety, and connections between policy and technology. The recommendations are as follows:

Continue to measure the safety benefits over manual driving. The experiment results showed that human drivers were, on average, safe drivers, but the AV driver was safer. The research team recommends continuing to measure the safety benefits of AVs as compared to human drivers. The research could expand to other metrics of safety.

Investigate further how traffic flow can be improved using ACC. The experiment results showed that ACC produces a smoother speed profile compared to human manual drivers. Further experiments could investigate the speed profiles of lower levels of automation, like ACC, in a more mixed automation environment.

Install a flasher or rear end sign on AVs, highlighting the fact that they maintain greater distances and stay stopped longer. The experiment results showed that the ACC and AV increased TTC as compared to the human driver as well as time spent at stop signs, which is an increase in safety. However, human drivers may expect a shorter TTC or that the AV will spend longer at stop signs resulting in rear ends of the AV. A flasher or rear end sign may alert the human driver to expect a longer delay from the AV and prevent rear end collisions.

Incorporate emissions testing into further AV simulation research. The experiment results showed a smoother speed profile which potentially could result in lower overall emissions. Future research could aim to quantify the emissions reductions from AVs compared to human manual drivers or compared to the various levels of automation.

Study best practices to alert human drivers for takeover. Preliminary test results showed human driver takeover time of 1-2 seconds when presented with a dashboard screen prompt to takeover the vehicle. Further research could investigate the incorporation of sound or seat rumble to alert the driver to takeover.

Research how lane keeping assistance can reduce near misses with pedestrians, cyclists, and motorists. The experimental result showed that lane keeping assist reduced lateral error by 5-10 times, which has implications for reducing near misses. Further research could investigate this further with respect to other road users such as pedestrians and cyclists.

Research Roadmap

The research team identified several opportunities to guide TxDOT in advancing infrastructure readiness, sponsoring new research and implementation programs, and strengthening partnership development.

Infrastructure

The highest priority of continued research is infrastructure, which enables TxDOT to focus on the physical environment within its direct jurisdiction.

- Focus on problematic roadway environments, particularly work zones and commercial vehicle inspection points.
- Prioritize a network of CAV corridors along major routes where TxDOT can concentrate its CAV investments. Include both closed-loop testing facilities and dedicated lanes in order to shepherd CAV technologies through the test, deploy, and scale process.
- Encourage national standards for key CAV roadway attributes, in particular lane striping degradation, signage clarity, and pavement quality.

Emerging Transportation Technologies

There are several complementary emerging transportation technologies that could potentially benefit the development of CAV systems. By sponsoring additional research, TxDOT can enhance public-private data sharing, improve asset management, and study human behavior.

- Leverage TxDOT's existing connected vehicle data framework to expand data sharing with the private sector and support connectivity opportunities: vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), vehicle-to-grid (V2G), vehicle-to-network (V2N), and vehicle-to-everything (V2X).
- Elevate research into high-definition mapping and digital twin technologies to support CAV operations as well as asset management.
- Expand human factors research to examine how the public will interact with CAV technologies and ensure that safety remains at the forefront.

Coordination & Partnerships

Collaboration is essential for the continued progress of CAV systems. TxDOT would benefit from streamlining its project management activities as well partnering with a diverse group of stakeholders.

- Establish a centralized CAV office with dedicated staff, who could serve as a single point of contact and coordinate across TxDOT Divisions and Districts.
- Urge researchers to foster interdisciplinary academic partnerships as well as engage with the public and private sectors.
- Identify grant opportunities where TxDOT could lead and/or support in order to position Texas competitively for federal funding.

Education & Workforce Development

TxDOT plays a significant role in informing stakeholders of the potential of CAV technologies. Further research should be conducted in education, training, and workforce development opportunities.

- Conduct trainings for law enforcement and first responders, and launch educational campaigns to raise awareness among the public.
- Inform policymakers of CAV safety and regulatory concerns, including steps to ensure that Texas continues to be a business-friendly environment.
- Assess the impacts of automation to the workforce and form partnerships with academic institutions to develop new curricula and programs.

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APPENDIX

Value of Research

In accordance with the scope of TxDOT Project 0-7033, the CTR has prepared an estimate for the Value of Research (VoR) associated with the research conducted over the course of the project. The functional areas deemed relevant and noted in the project contract encompass both qualitative and economic areas. The four functional areas identified for the ODD Project 0-7033 are summarized below.

Table 1: Functional Areas

Selected	*Functional Area*	*QUAL*	*ECON*	*Both*	*TxDOT*	*State*	*Both*
	Level of Knowledge	X			X		
	Management and Policy	X			X		
	Traffic and Congestion Reduction		X			X	
	Safety			X			X

Level of Knowledge

CTR performed a qualitative assessment on the operation of autonomous vehicles (AVs) in different operational design domains (ODDs) and determined that CAVs aid TxDOT in:

1. Creating a common framework for discussing what ODDs for AVs are and providing a robust framework of a suite of possible ODDs.
2. Outlining the various federal and state policies regarding AV deployment and operation to better inform TxDOT and other policymakers on decisions regarding AVs.
3. Providing research on human driver experience and behavior as compared to an AV on simulated roadways to safely assess operational differences to inform decision making.

This improved level of knowledge can be utilized to inform decision making surrounding the deployment of AV technology on TxDOT roadways.

Management and Policy

The research conducted for the Texas Department of Transportation (TxDOT) under management and policy for defining the ODDs of AVs has yielded qualitative value through a multifaceted approach. A critical aspect of this contribution lies in the development of a robust outline of existing federal and state policies on AVs. By meticulously analyzing and outlining the regulations and policies surrounding AVs, the research not only ensured alignment with the broader legal landscape but also identified gaps and areas needing refinement. This comprehensive understanding of the regulatory environment can be used to shape TxDOT's management and policy initiatives, providing a solid foundation for crafting nuanced policies and guidelines specific to the various ODDs of AVs. The integration of these insights into the research framework underscores the project's qualitative significance in navigating the complex regulatory terrain surrounding AVs.

Traffic and Congestion Reduction

According to the results of the 0-7033 research project, the AV had on average a mean delay travel time less than that of the human drivers. This means that the AV drove closer to the theoretical travel time achieved at free flow traffic speeds. The closer that traffic is to free flow, the less congestion there is on the roads and the results imply that AVs can reduce congestion by driving more efficiently than human drivers. To quantity the savings in congestion costs, data from the 2022 INRIX Traffic Scorecard, the Texas Comptroller's Office, and an estimate of a 0.1% reduction in time lost in congestion for AVs yields a cost savings of $20.4 million from the following calculation.

Savings = 0.1%*(51 hours)*($16.89 / hours / driver)*(23.7 million Texas drivers) = $20,414,943

Safety

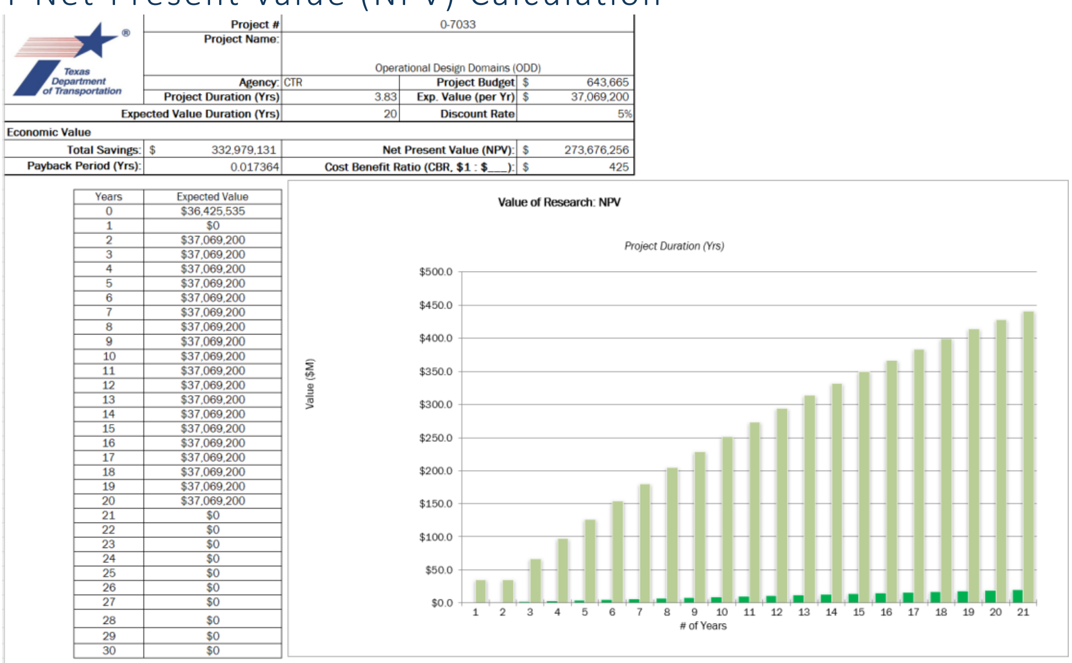
According to the research, the AV was safer than the human driver. The National Safety Council in the United States has developed a guide to calculate the average costs associated with motor-vehicle injury based on accident severity. These average cost estimates account for the calculable costs of motor-vehicle crashes are wage and productivity losses, medical expenses, administrative expenses, motor-vehicle damage, and employers' uninsured costs. To estimate the total monetary cost of motor vehicle accidents in Texas, the research used the TxDOT yearly report on "Urban and Rural Crashes and injuries by Severity for 2022." The costs of all these items for each death in 2022, total number of crash types in Texas, and total cost of crashes in Texas were:

Table 2: Average Economic Cost by Injury Severity or Crash, 2021

Crash Injury Severity	Cost	Crashes	Total Cost
Death (K)	$1,778,000	4,037	$7,177,786,000
Disabling (A)	$155,000	15,299	$2,371,345,000
Evident (B)	$40,000	66,405	$2,656,200,000
Possible (C)	$24,000	84,088	$2,018,112,000
No injury observed (O)	$6,700	362,808	$2,430,813,600
Total			$16,654,256,600

Assuming a conservative estimate of 0.1% reduction in traffic crashes across all severity types by the deployment of AVs, the total cost savings would be $16,654,256.60.

TxDOT Net-Present Value (NPV) Calculation



Project #	0-7033		
Project Name:	Operational Design Domains (ODD)		
Agency:	CTR	Project Budget	$ 643,665
Project Duration (Yrs)	3.83	Exp. Value (per Yr)	$ 37,069,200
Expected Value Duration (Yrs)	20	Discount Rate	5%
Economic Value			
Total Savings:	$ 332,979,131	Net Present Value (NPV):	$ 273,676,256
Payback Period (Yrs):	0.017364	Cost Benefit Ratio (CBR, $1 : $___):	$ 425

Years	Expected Value
0	$36,425,535
1	$0
2	$37,069,200
3	$37,069,200
4	$37,069,200
5	$37,069,200
6	$37,069,200
7	$37,069,200
8	$37,069,200
9	$37,069,200
10	$37,069,200
11	$37,069,200
12	$37,069,200
13	$37,069,200
14	$37,069,200
15	$37,069,200
16	$37,069,200
17	$37,069,200
18	$37,069,200
19	$37,069,200
20	$37,069,200
21	$0
22	$0
23	$0
24	$0
25	$0
26	$0
27	$0
28	$0
29	$0
30	$0

Figure 1: NPV Analysis